NASA TECHNICAL MEMORANDUM

NASA TM-88485

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ROCK FLOWS

S. N. Matveyev

Translation of "Kamennyye potoki," IN: Problemy fizicheskoy geologii, No. 6, 1938, USSR Academy of Sciences, Moscow, pp. 91-121.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546   DECEMBER 1986

1. Report No. TM-88485	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ROCK FLOWS		5. Report Date December 1986
		6. Performing Organization Code
7. Author(s) S. N. Matveyev		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address THE CORPORATE WORD 1102 ARROTT BUILDING PITTSBURGH, PA 15222		11. Contract or Grant No. 4006
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION WASHINGTON, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Kamennyye potoki," IN: Problemy fizicheskoy geologii, No. 6, 1938, USSR Academy of Sciences, Moscow, pp. 91-121

16. Abstract

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17. Key Words (Selected by Author(s))	18. Distribution Statement Unrestricted-unlimited		
19. Security Classif. (of this report) unclassified	20. Security Classif. (of this page) unclassified	21. No. of Pages 51	22. Price

ABSTRACT:

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ROCK FLOWS

S. N. Matveyev

Rock flows are defined here as forms of independent mass /91* movement (W. Penck's "spontane Massenbewegungen") commonly found in mountainous countries. There is interest in investigating them primarily because they represent the most convenient object for quantitative study of mass movement processes and for study to establish the balance of erosion. Related on the one hand by a whole set of transitional forms to other mass movement phenomena -- screes, rockslides, landslides -- and on the other to mass transfer phenomena (Penck's Massentransport) -- mudflows, glaciers -- they would seem worthy of investigation at least as thorough as that for all these phenomena.

In glacial-morphological investigations of mountainous regions, rock flows merit at least as much attention as morainic formations: confusion of these forms, which often occurs both in literature and in cartographic materials, results in false paleographic constructs.

Study of rock flows is of considerable interest also from the standpoint of engineering geomorphology. Forward movement of rock flows results in damage to and destruction of the roadbeds which they intersect -- a phenomenon which must be taken into account when routes in mountainous regions are being planned.

During economic development of mountainous lands, thorough study of rock flows is also necessary for the following reason: furrows ("gullies") on mountain slopes occupied by rock flows often become the paths of avalanches, while segments of the

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*Numbers in the margin indicate pagination of the foreign text.

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upper areas of slopes and plateaus (regions which feed avalanches) are often occupied with so-called "rock seas." When anti-avalanche structures (stone retaining walls, etc.) are being planned, preliminary stationary investigations of the movement of these rubble segregations are necessary to prevent possible damage to or total destruction of protective structures.

During economic development of mountainous lands, specifically construction in mountain valleys framed by rocky walls, construction sites must be carefully selected with the understanding that points which are not directly threatened by rockslides may still be caught up in the most destructive rubble flows from remote rock cliffs, which spread for kilometers over a nearly flat, horizontal surface.

Despite significant theoretical and practical interest in /92 the study of rock flows, despite their wide distribution in mountainous regions, especially in areas dominated by subnival and semiarid climates, these phenomena remain inadequately studied.

Thus, no one has studied the movement of Falkland Island rock rivers, which have astounded all travelers by their grandeur. The rock rivers of the Urals have been described only in the most general terms and remain unstudied (in terms of their genesis and movement), although they were the object of an excursion of the 7th Geological Congress. Siberia's rock streams are almost entirely unstudied. And, finally, even less known are flows of dry insolation gravel, which apparently play a tremendous role in the denudaton of arid lands.

I

Formations considered in the first section of this article are known as "rock rivers," "rock flows," "boulder flows," "boulder stria," "gravel flows," "rock seas," and "rubble seas."

All these forms, quite varied in both appearance and in the nature of their rubbly material, are characterized by a common origin. They appeared as a result of the segregation of material created by the **normal processes of rock formation.**

The classic example of rock flows are the Falkland Islands' majestic stone rivers, "streams of stones" described after personal observation by Perneti[*], Darwin[**], Thomson[+], and Anderson[++].

In his "Journal of Researches," Darwin describes the stone rivers of the Falkland Islands. "In many parts of the island, the bottoms of valleys are covered by myriads of large sharp fragments of quartz rock forming 'stone rivers.' Every traveler since Perneti's time remembers them with astonishment. These fragments are not eroded by water; their corners are only slightly rounded....

"One cannot measure the thickness of the layer they form, but one can hear how the water in small rivulets flows between the rocks several feet below the surface. The width of these stone stria varies from several feet to a mile...

"The most remarkable feature of the "stone streams" is the slightness of their slope... On this uneven surface it is impossible to measure their slope, but to give a general picture, I can say that this slope would not slow the speed of an English mail coach..."

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[*] French naturalist who participated in Bougaineville's expedition and visited the Falklands in 1764.
[**]Darwin's descriptions from 1833 and 1834.
[+] W. Thomson, head of the Challenger expedition (1872-1876).
[++]Head of a Swedish expedition in Antarctica. Worked in various parts of the Eastern Falklands in 1902.

According to Darwin and Thomson, quartz boulders in stone rivers measure from 3.5 to 7 m in cross section.

In the Falkland stone rivers, one can almost always distinguish the main flow from tributaries which enter it mostly at right angles. The stone rivers' lengths vary greatly, reaching several kilometers. The stone river Darwin, described by Anderson, reaches 5 km in length.

In the middle of these rubbly masses, most often close to the edges, peat soil has hardened wherever boulders lie sufficiently close to one another. Thus, these stone rivers have islands of peat. These islands, covered only by scrub, reach 4-8 m in width and 6.5-16 m in length according to Perneti.

After the Falkland Islands' boulder flows, the most grandiose of those known so far are in the Urals, on Mount Taganay and close to the Bakal Mine.

There, just as in the Falklands, these flows consist of huge quartzite boulders. Tschernyschew described their most general features, without trying to explain their origin.

Rock flows of the Urals south of Zlatoust have been described by Kler. In his words, the panorama of a large and well developed system of rock flows greatly resembles a group of glaciers. From the top of Malyy Yamantay, "We see a certain similarity to ice fields -- these are simply huge terraced areas covered by a chaotic mass of rocks; from these reservoirs, as from ice fields, the alluvial deposits which gradually compress and take the form of glaciers have their beginning." Several such rock flows, united into a large stone river, often penetrate far into the nearest valley.

Without describing the morphological features of stone flows (which greatly complicates their comparison to other

types), Kler notes that they "do not serve as a channel for rock flows and display no traces of the action of water." The erosion of the surface of stone rivers and the fact that places where roads intersect with stone flows are subject to rapid deterioration are evidence of flow movement. However, the rate of movement there has not been measured.

Stone rivers and flows, quite common in the Urals, are well developed particularly on flatter slopes. Stone rivers with bare, unvegetated surface, descending from forested slopes, were observed by Varsanov'yeva [33] at several points in the Northern Urals.

Comparatively rich material relating to rock flows exists for the alpine zone. Almost all valleys on Spitsbergen have complex streams of boulders resulting from the mersion of stream-forming stria of slope boulders. But here boulder streams do not achieve their real development, and final transport of rubbly material occurs via flowing water (rapid when the snow cover melts) or glaciers.

According to Högbom, real, well-developed boulder streams are unknown in alpine Scandinavian regions [17, 18]. Boulder stria (Blockstreifen) rushing downward along slopes are relatively short and broad and occur almost everywhere in the Regio alpina of Scandinavian mountains. Högbom tells of similar boulder stria even in the coniferous forest area of Norrland, where, however, they do not occur as often as in higher zones. /94 In Högbom's opinion, these rubbly stria are the first "sources" of large boulder streams (Blockströme).

I. N. Gladtsin described stone flows in the Khibinsk Mountains in very general terms [1], but did not study them specially. The USSR Academy of Sciences Institute of Geography has been conducting stationary observations of certain Khibinsk
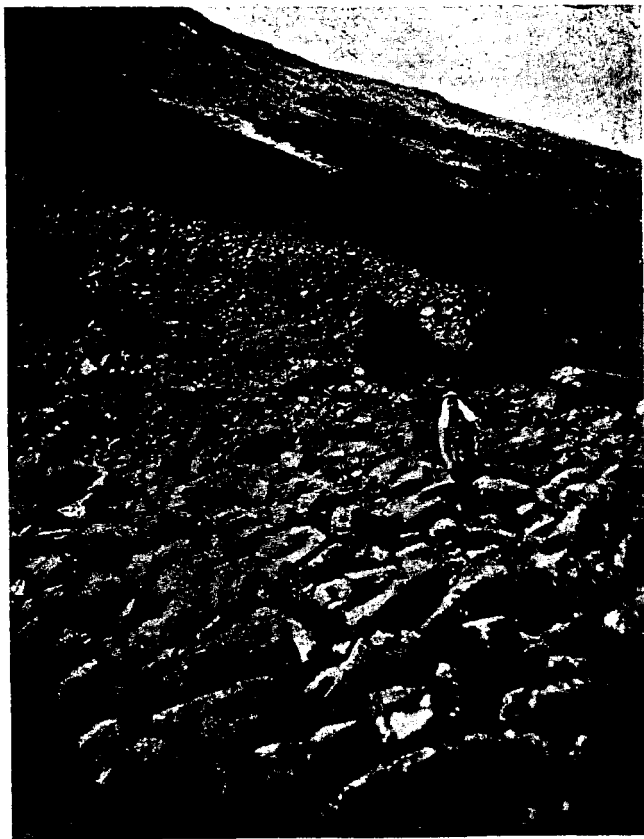
Fig. 1 Rock steam on the slope of Poachvumchorr (Khibina) at its termination (photo by E. G. Vokken).

Mountain stone flows near the Academy of Sciences' mountain station since 1934.

The rubbly segregations which interest us usually take the form of boulder stria similar to those described by Högbom in the Scandinavian mountains. The steepness of the Khibinsk Mountain slopes and the presence of strong currents at the bottoms of mountain valleys has prevented development of real stone rivers here.

In the area around the Academy of Sciences' mountain station, several such bare stone stria, which descend via clearings in the forested slopes of Poachvumchorr, have been studied. Usually 5-10 m wide and occupying pronounced trough-shaped trenches, these stria-shaped segregations of rubble are pronounced on 30-50° slopes. The dimensions of surface gravel vary widely: from relatively small fragments (1-5 cm in cross section) to sharp boulders 0.5-1 m in cross

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Fig. 2 Termination of the same rock stream, which enters the Seytis"yavr in two lobes.

section (fig. 1 and 2).

In contrast to high-altitude regions which yield relatively rich material for observation of forms of mass movement, the Alps have provided relatively sparse information in this area.

After A. Chaix's [11, 12] information on boulder streams in the Swiss National Park (see below), Waldbauer [30] described rock flows of the Oberengadin. Material in these streams is less coarse than in boulder streams (Blockströme) and rock seas and is not as well sorted as in boulder and rock stria (Blockstreifen, Steinstreifen).

Information on rock flows in the mountainous regions of Asia is quite scarce. Rock streams of Siberian mountains are completely unstudied. Data on them is found in works of only a few researchers.

V. A. Obruyev describes a quartzite stone river several hundred meters long and several tens of meters wide, descending along the slope of a bald peak in the Olekminsk-Vitimsk mountain country.

According to Edelstein, stone rivers play a quite prominent role in the morphological landscape of certain parts of bald peak regions in Minusinsk Kray. Here, especially where bedrocks are quite varied (granites, gabbro-diorites, etc.) accumulations of rubbly material covering the highland plateaus descend more or less in long tonques to the upper reaches of mountain valleys.

L. I. Semikhatova [35] recalls stone rivers in the Altay /96 State Preserve (alluvial granite deposits covering the slopes of the Korbu Range and forming stone rivers extending along the slope of a bare peak in the uplands of the Syk-Tyzyl River (left tributary of the Great Abakan). The author of this article saw a stone river of huge, sharp boulders descending in a wide clearing along the forested slope of a cone-shaped hill on the left bank of the Samargi River in Sikhote-Alina.

As regards Central Asia, gravel streams of the Central Tien Shan were described by Friederichsen [14]; of the Western Tien Shan, by Machatschek [21].

K. K. Markov reports on the frequency of rock flows filling the dry ravines of the Eastern Pamir and the alpine part of the Western Pamir.

Without explaining Perneti's and Darwin's old hypotheses on the origin of stone rivers, which consider the Falklands' gravel streams to be caused by volcanic and seismic phenomena, we will consider newer theories.

Let us note first that none of the researchers who have observed the morphological features of stone rivers described above has tolerated ideas of the possible transfer of these sharp, frequently huge fragments by water.* Slight inclinations

* Darwin says that fragments in one valley south of Berkeley Bay were so large that, surprised by a shower, he took shelter beneath one.

of a locale intersected by stone rivers, not exceeding 6-8° on slopes and 2-3° in valleys, as well as the absence of denuded screes eliminates the possibility that these rubbly segregations were formed by regularly falling fragments or by catastrophic rock slides. These segregations lack features which, according to W. Penck, characterize rock slides [32].

The possible glacial origin of stone rivers was considered quite questionable by researchers who visited the Falkland Islands: the Falklands do not exhibit signs of diluvial glaciation.

The hypothesis of the glacial origin of Ural stone rivers, stated in a cautious and rather ambiguous form by Kler [13]* is contradicted primarily by the fact that the area where the stone streams described by Kler develop lies outside the boundaries of diluvial glaciation.

In 1877, Thomson [28], decisively rejecting the glacial origin of stone rivers, attributed their appearance to two major factors: 1) weathering and 2) independent soil movement. Thomson presented his process as follows. Fragments of quartzite emergences, isolated by weathering and falling to the surface of peat soil, are quickly covered by vegetation and thus are incorporated into the soil.** This surface soil layer, /97 called a "soil cap" by Thomson, is in infinitely slow motion. The major cause of the movement is the alternate drenching and drying of peat soil, which causes its alternate expansion and

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* Accused that his observations were inadequate, Kler hypothesizes that "Ural stream-like alluvial rock deposits are a phenomenon homologous to glaciers, only different in appearance..."

**Peat formation occurs quite rapidly on the Falkland Islands, and peat soils are common everywhere there, even covering the islands' high areas.

contraction. According to Thomson, the soil cap slowly moves
down a slope toward the valley floor, where a current, washing
away soil particles, exposes the boulder segregation.

Thomson presented his view of the origin of stone rivers in
pieces. On the one hand, he did not assign himself the task of
writing an exhaustive tract on this phenomenon; on the other,
the theory of mass movements (Massbewegungen) had only just been
created at that time.

Thomson's theory in a somewhat modified form was later used
by A. Leppla [20] to explain the genesis of Taunus (Gunsryuk)
boulder segregations, which exhibit a startling similarity to
Falklands boulder streams.

Leppla calls these boulder segregations "Schuttströme" or
simply "Ströme." In their majestic appearance, Falklands
boulder streams are, however, hardly superior to those of
Gunsryuk, although the latter sometimes reach significant size.
Boulders in both places are of different magnitude and for the
most part have sightly blunted ridges. There, just as on the
Falkland Islands, the slope of the surface occupied by quartzite
boulder segregations is slight: slopes composed of clay shale
have only a 2-3° grade. There have been no direct studies of
the movement of Falklands boulder streams, and, because of the
lack of denudations, even indirect signs of movement -- traces
of the mechanical action of boulder accumulations on the bed
they occupy -- cannot be established. There is a sort of
indirect indication of movement for Gunsryuk boulder streams:
Leppla observed a typical elbow-shaped bend, "Hackenwerfen," the
disruption and shift of clay shale seam outcroppings.

Gunsryuk highlands, just as the Wickham Mountains (East
Falkland), are composed of quartzites and quartzite sands
deposited on clay shales. Fallen quartzite boulders pile up
mostly at the base of the steepest slopes. On the Falklands,

they fall onto peat soil; in Gunsryuk, on the surface of
weathered clay shales which have a certain plasticity when wet.
In both cases, according to Thomson's and Leppla's hypothesis,
rubbly masses falling onto slopes are in sliding movement,
following the lines of the greatest grades to ultimately form
segregations in valleys. The only significant difference is
that boulders in the Gunsryuk slide over damp clay bedding,
while on the Falklands they are transported in the peat mass.

Conclusions reached as a result of the development of the
theory of mass movements by Davison (1888), Rayer (1888),
Blankengorn (1896), A. Penck (1894), and Götzinger (1907)
provided the basis for Anderson's hypothesis, in which he
attempted to explain the occurrence of the Falkland boulder
streams by modern solifluction processes.

In Anderson's opinion, these majestic stone rivers occurred
at a time when the South American continent was exposed to
glaciation, and a cold climate with intense frost weathering   /98
and arctic solifluction predominated on the nearby Falkland
Islands. Anderson also considered Urals boulder streams
described by Cherbyshev [29] as mineral.

Further progress in the study of mass movements,
particularly the study of solifluction processes, makes it
possible to present a more complete picture of the genesis of
rock flows. Let us deal first with the causes and forms of
movement.

The development of the movement of masses ready for
denudation and the maintenance of this movement are caused by a
whole series of factors, including:

I. An increase in weight.
    1) An increase in weight due to accumulation of rubbly
material;

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2) An increase in weight due to water absorption by the segregated masses.

II. A change in the matter's volume:

1) Changes in volume caused by temperature fluctuations:

a) Changes in rock fragment volume;

b) Changes in water and ice volume in interstices between fragments.

2) Changes in volume due to swelling and shrinkage of colloids during drenching and drying.

Water apparently takes part in rock stream movement everywhere except in completely arid regions (see below). Most researchers note the presence of flowing water in the depths below rubbly masses of rock streams.

This water store is maintained and augmented both by drenching from above by rain and melt water and, probably, by water vapor condensation. In addition, one other possibility must be kept in mind: a thick mass stream rapidly deepening the bottom of the corrosion trench it occupies may expose the ground water level.

Thus, movement in most rock streams has a mixed nature:

1) Partial Massentransport (W. Penck), at least in the periodic transport of fine water particles; 2) partially Massenbewegungen. The latter type of movement can be accomplished simultaneously by:

A. Bound movement of fragments as parts of a single system.

Flows of fragments along a loose bedding.
Sliding along wet clay bedding.

B. Free movement of individual   Sliding of separate
   elements of rubbly masses   fragments.

                                      Rolling of separate
                                      fragments.

                                      Vertical movement of
                                      individual elements.

Movement is periodic (see below) and is apparently accomplished in jumps.

W. Penck describes the process by which a mass flow occurs as follows [23].

When the paths of neighboring rocks are combined, specific lines are chosen for many varied reasons. If loads greater   /99 than those at neighboring locations shift along this combined path of movement for a long time, lines of movement due to increased mechanical action on the base deepen and become furrows. An increase in loads moving in a furrow causes it to further deepen, etc. Individual actions are not only added, but intensified. A mass flow (Massenstrom) must occur where, sometimes, due to the combination of movement paths of neighboring individual particles, one chosen path of movement has arisen. As the mass flow moves, the deepening of the segment of the base along which it moves is also necessarily related to its development in the valley-like depression (the German authors' Talungen).

Gravel accumulated in large masses within its path of movement acts as a heavy plane on the base along which it moves (W. Penck [23]).

The moving gravel is a mixture of coarse fragments of different sizes, fine-grained elements, and clay components. As a result of the more or less complete washout of fine elements, coarser fragments build up on the surface. If rock in the

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region which feeds gravel streams is predisposed to break onto large boulders, the latter pile up on one another. Thus we have a typical boulder stream (Blockström) pattern.

Flat-hilled locales whose depressions are not occupied by strong currents are most suited for formation of entire boulder stream systems. Högbom [17] points out that, during solifluction phenomena, individual boulders can move much more quickly than all the rest of the flowing gravel mass underlying and surrounding them, which they literally plow up. Individual moving boulders are combined into boulder stria, and actual boulder stream systems may ultimately arise, shifting on the moving bedding. The presence of this type of bedding was established in Falkland Islands rock rivers. This bedding is clay rich in rocks. It seems unlikely that, lying on an inclined base, this bed would be immobile during drenching. But if it does move, the boulders on top of it should also move.

Solifluction acts even now on the Falkland Islands. Its manifestations are observed wherever a more rapid process makes movement more noticeable: on slopes (more than 10° grade) of broad, small valley-like depressions. The movement of mainstreams which occupy the flatter valley floors is quite slow and imperceptible. Here rubbly masses build up, and water also accumulates. Its action here on bottomlands should be much more powerful than on valley slopes. On slopes, water is completely taken up by rubbly masses and absorbed by them. These masses move in a sort of water-saturated state as a single whole (Massenbewegungen-like movement). There is an excess of water, which carries off fragmental mass elements on valley floors, /100 but, given the floor's small grade, it is insufficient to move large boulders.

The typical distribution of boulder streams, namely their confinement to valley floors, shows only that the quantitative relationship of fine-grained materials to water is different in

valley bottoms than on slopes. As W. Penck stresses, this distribution does not at all prove that these formations are minerals.

As regards Urals boulder streams, Kler's data [13] on the presence of "frozen layers of earth at a certain depth" and on the existence of "ancient snow and frozen soil deposits more or less covered by gravel and rock" in high massifs make it possible to conclude that solifluction processes play just as important a role in the movement of these stone rivers.

The sphere of action of solifluction -- a factor of tremendous importance -- is limited in the modern era to high latitudes and alpine regions. In areas with higher average annual temperatures, solifluction turns into processes of gravel flow (Schuttfliessen), arising wherever gravel is sufficiently wet and manifest more intensely, the more colloidal substances are involved in them.

On the basis of data from Sven Hedin [15] and M. Tafel [27], we can state that gravel flow processes are extremely developed in Central Asia. The phenomenon of gravel "flow" is apparently developed on a grand scale in Tibet, where it is related to the onset of monsoon rains and snow melting.

Note that, in addition to flow of drenched gravel, in Central Asia gravel also moves slowly in a dry state, which constitutes a more common, more important form of denudation. W. Penck notes that free mass movements (freie Massenbewegungen) without water are very common particularly in completely arid and semiarid regions, and they constitute the dominate form of denudation on slopes flatter than 25°. W. Penck emphasizes that these dry mass movements have so far received little attention, although they are a universal phenomenon in arid regions and are of greatest importance as a factor in denudation.

Detailed investigations of conditions for formation of dry insolation gravel and its slow movement were conducted in the Atacama Desert and in the semiarid areas surrounding it. By the way, that rubbly masses move is often confirmed by the complete roundness of fragments due to mutual friction. The very distribution of rubbly segregation elements in their vertical profile also indicates movement: heterogeneous rubbly material (gravel, grus, sand, dust) is uniformly mixed right down to the base on which these masses lie. But insolation formation (W. Penck's Insolationsaufbereitung) acts only on the gravel surface. Therefore, only the components on its upper horizons are crushed. Thus, crushing permeating right to the bottom of often very thick gravel masses presumes mixing, i.e. movement. /101

Investigation of the petrographic composition of gravel reveals that it moves down along a slope. Movement is planar on slopes; linear in furrows. In these furrows, which lack any trace of the action of flowing water, gravel segregations take the form of thick streams. The grade of furrows occupied by gravel streams is always less than that of the surrounding slopes. Studies show that highly mobile sand-grit masses arising due to insolation formation should be in motion as long as the surface grade is 2-3°. Studies also show that gravel streams of Puna de Atacama themselves dig their own channels and deepen them in valley-like depressions or at least play a major part in this process.

Literature available to us contains no indications of any measurements of the speed of rock flows in this group (see below for measurements of the speed of rock flows of the rock-glacier type). Let us present certain results of stationary observations conducted by the Khibinsk unit of the USSR Academy of Sciences' Institute of Geography. Methods used to study movement were the following. Two straight lines were transversely aligned on each gravel stream selected as the object of observation (on two typical stream segments), and two

rows of stones along them were painted. At the ends of each painted line stakes were set (on a slope outside the stream bed).*

Markers placed in June 1934 on two gravel streams on the slopes of Poachvumchorr were checked in August 1935 and June 1938. The inspection did not reveal movements of a mass nature. We presume that these results are due not so much to the nature (slowness) of movement as to the imperfection of the measuring technique used.** That straight solid lines of painted stones were disrupted (as a result of the displacement of individual fragments relative to one another), makes it quite difficult to make a case for weak bending of these lines, which would have had to occur due to bound movement of rubbly masses as part of the single system.

We assume that obtaining more satisfactory results requires recording the position of the painted lines by repeat photogrammetry during different seasons of the year. The necessity of this last condition is dictated by the peculiarities of the processes by which rock and mass movements are prepared.

Processes of rock formation, which create the rubbly material of rock flows and processes by which the masses formed move, are not continuously active.

All climatic zones have isolated periods of movement and /102 periods of rest during the year. Frost weathering, one of the

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* Markers placed in different years were coated with different paints. Red lead was used on those placed in 1934, lake in 1935, and green paint in 1936.
**Rock flows which were observed are not immobile. The denudation of their surface and the friable, quite unstable placement of rocks and boulders demonstrate this.

strongest factors in mechanical formation, acts in the polar
zone in winter; in subarctic zones, in fall and spring.

In zones where colloidal products of weathering form, humid
seasons are the periods in which formed masses shift. In dry
seasons these processes come to a standstill. In semihumid
zones with a distinct dry season, insolation formation then
begins to act, but masses remain immobile due to mixing with
dense (when dry) colloids. Transitions from dry to humid are
periods when masses on slopes move due to frequent changes in
volume from swelling and shrinking of colloids. In the
semihumid zone these periods occur twice a year; in moderate
zones, more often, spreading less correctly over the entire
year. In semiarid zones, gravel drenching periods are periods
of active mass shift ("gravel flows" in the Tien Shan, in
Eastern and Southern Tibet, Karakorum, etc.).

"Thus," says W. Penck, "If we wish to study mass movements
anywhere in Central Europe, it should be done in early spring or
fall; in the Mediterranean region in winter; in semihumid
tropics in summer. Only then can the signs of mass movements be
detected in these zones."

The periodic nature of manifestation of mass movement
predetermines the time interval which can be used as the
shortest unit of time to study these motions in general and the
movement of rock flows in particular. Processes of rock
formation and of mass movements are the result of the action of
various forces, each of which acts with an intensity inherent to
it at any given time. As was shown, this intensity has an
annual period, which can be regarded as constant from one year
to the next. However, we observe not the action of each
individual variable factor, but only the total action of all
forces manifest during a year. Hence, a year is the shortest
unit of time during which all factors in rock formation and
denudation act at least once in their own specific ways.

There is no essential difference between boulder segregations, which are usually called "rock seas" or "stone seas" ("Felsmeere," "Steinmeere"), and rock flows. The latter simply extend in one direction more than in others. Boulder seas are regarded as: 1) mineral formations or 2) as a phenomenon attributable to climate. Thus Lozinski regarded boulder seas in German medium-altitude mountains as products of mechanical, namely frost, erosion which predominated during diluvial glaciation in the extra-glacial regions of Central Europe. Because of their similarity to modern boulder flows of the polar zone, B. Högbom and V. Salomon considered these boulder segregations as diluvial boulder flows occurring in /103 similar fashion and also moving, but no longer being formed. In I. N. Gladtsin's opinion [1], "Rock streams and stone seas are creations of frost erosion. In regions with harsh climate, where frost erosion occurs, they form even now. In regions with moderate climate, they are relicts of the Ice Age."

However, although certain facts also indicate that formation of certain boulder seas pertains to the geological past, as W. Penck stresses, there are still no grounds to relate their occurrence to the Ice Age or to one of the stages of glaciation. In most cases it turns out that these boulder segregations form and move now just as in the past. That the formation of boulder seas is not confined to a certain type of climate and is not exclusively related to the region where mechanical frost erosion predominates is obvious from a whole series of facts. This is evidenced primarily by their geographic distribution. W. Penck saw boulder seas in Uruguay on steep slopes of insular mountains constructed of granite and syenite or quartzite and on slopes in the highlands of Western and Central Anatolia, consisting of serpentinite and andezite. In exactly the same way, boulder seas of German medium-altitude mountains with a tendency to break up into boulders are found on

slopes of a certain grade (15-30°). Studies of boulder seas in
Fichtelgebürge, Hartze, and Odenwalde showed that:

1) Rubbly material resulted from chemical erosion;

2) The tendency to break up into boulders is a specific
property of certain types of rock;

3) The rocky base on which boulders lie is the region which
feeds boulder segregations.

The existence of trees rooted between boulders indicates
the movement of these rubbly segregations -- they frequently
lean or are crushed. Movement takes the form of a passive shift
of the upper layer of boulders along the clay-gravel bedding.

According to A. A. Grigor'yev, alluvial rock deposits play
an extremely important role in the terrain of the northeastern
part of the Kola Peninsula. There they occupy the floors of
basins and wide valleys, the declivities of terraces and their
plateaus. Some of these alluvial deposits are undoubtedly an
"erosion crust formed at the site, whose origin is apparently
related to processes of frost erosion and selective
denudation." Other alluvial rock deposits have resulted from
selective removal of fine soil from a moraine very rich in large
rubble (A. A. Grigor'yev [2], 1932).

In high latitudes and in alpine regions, rock seas
obviously form primarily due to frost erosion processes. Arctic
boulder seas form as a result of the breakup of the flat rock
surface. However, there are homologous formations also on
slopes, and all forms in transition to steep mountain slopes,
with their accumulation of talus, are observed there.

In subarctic regions of northern Sweden, boulder fields
(Högbom's Blockfelder) are quite common. They occupy an area of
many hectares or even square kilometers and, along with   /104
marshes, are the most impassable locales. These rock fields,

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which cover large areas, are for the most part considered
segregations of morainic boulders, especially in the northermost
parts of Swedish Lapland. In many cases, however, more detailed
investigations prove that they are broken-up rock surfaces which
correspond to boulder fields of arctic lands and alpine regions.
Boulder fields which unquestionably come from moraines are also
common. However, they rarely are extensive. Högbom calls
autochthonous those boulder fields which are characterized with
rubbly segregations with common petrographic composition and
base rock and which lie in situ or shifted as a result of frost
relative to this rock base -- in contrast to glacial
segregations of morainic boulders. For the most part, boulder
fields have a level surface. We should assume that this
leveling results from sliding of boulders. Masses of boulders
form only the very surface cover. The gravel material lying
beneath it is usually wet. Often, water even stands between the
boulders. This circumstance causes intense manifestation of
frost erosion processes and frost shift. The presence of
typical structural formations on boulder fields (stone networks,
etc.) indicates this.

Boulder fields, which are often completely horizontal
surfaces stretching for many hectares, also form inclined
surfaces. Känttö, where a boulder fields extending 500 m drops
about 5 m, is an example of this. In this case, one must speak
rather of a boulder flow.

In conclusion, let us mention one possible case of the
conversion of typically developed rock seas, i.e. seas covering
flat crests, into typical rock flows. Sooner or later, because
the edge of the plateau recedes due to erosion and denudation
(particularly falls), rock seas are also caught up, and their
rubbly material is then more or less involved in rapid movement
and forms scree and rock flows on slopes. Thus, apparently, one
can explain the formation of certain rock flows, particularly in
the Khibinsk Mountains.

So-called rock or gravel glaciers (Blockgletscher, Schuttgletcher, glaciers rocheux) constitute a special group of rock flows. They were first studied in 1909 by Capps [10] in Alaska. Ten years later these same formations were discovered and described by A. Chaix [11] under the name "coulées de blocs" in Switzerland. Typical characteristics of the forms of these categories result from their common origin. Rock glaciers, successors to real glaciers, often begin in cirques, occupy the bed of glacial valleys, and consist of morainic material, under whose cover ice may be preserved. A whole series of transitional forms relates this group, on the one hand, to /105 gravel flows in our first category and, on the other, to actual glaciers. Alaska's rock glaciers, described by Capps, occupy cirque-shaped valleys lying on the edge of the nival zone, and they often have small glaciers at their peaks. Most such rock glaciers fall into the main valley of the region studied, which is occupied by the Great Kennicott Glacier. Rock glaciers are varied in form. Some have a wide, fan-like peak, shifting downward into a narrow tongue. Others, narrow at the top, expand downward into spade-like lobes. Most are relatively narrow bodies 1 to 4-5 km long. The grades of rock glacier surfaces vary from 9 to 18°. Rock glaciers consists of sharp fragments of rock -- porphyries, limestones, greenstone rock, clay shales -- constituting the cirques' walls. Fragments are small in most cases. The average diameter of porphyry fragments is about 15 cm; fragments of greenstone rock and limestone, larger; clay shales, smaller.

In appearance and position, rock glaciers resemble actual glaciers. Their cross section is convex, rises along their axes, and descend sharply toward their edges. Longitudinal ridges separated by depressions are typical surface forms. Longitudinal ridges become more relief-like toward the lower end of rock glaciers and give way to concentric ranges or ridges

parallel to the lower end of the rock glaciers. The grade of the frontal slope of rock glaciers is often nearly the largest slope of their rubbly material.

Seven or eight drillings in rock glaciers performed by Capps each revealed ice -- not a solid ice mass, but filling the interstices between sharp rock fragments and forming with them a unique brecchia. The depth at which ice was found varied depending on the absolute height of the rock glacier's position and on where in the rock glacier drilling was performed. Toward the lower end of rock glaciers, ice apparently lies too deep to be detected by shallow drilling. Closer to a cirque, the ice in rock glaciers is usually detected 1 or 2 feet from the surface. One can often easily obtain drinking water by drilling at points where one hears the rush of a current below. Drilling at these points has shown that water streams among fragments made by ice.

Within the limits of Capps' study of the Alaskan territories there is a whole set of transitional forms between typical rock glaciers and actual glaciers. Nonetheless, there are also indications of a sharp difference between one and the other. Most rock glaciers begin in cirques, where all, or almost all, winter snow melts in summer. Rock glaciers do not exhibit surface cracks and grooves. Rock glacers moving forward in a fashion similar to actual glaciers, unlike the latter, never recede. Furthermore, rock glaciers retain their integrity even if movement stops.

Capps proposed the following hypothesis on the origin of the rock glaciers of the Alaskan territory he surveyed. At the end of the last ice age, glaciers receded in most small valleys, /106 and the area of permanent snow fields in cirques shrank. The exposed walls of cirques were engulfed by intense erosion processes. Products of erosion, transferred by glacial ice, accumulated in abundance at the ends of the glaciers. Melt and atmospheric waters, penetrating the rubbly masses which had

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overflowed the lower ends of small, dying glaciers, froze there and filled interstices between fragments with ice.

In these rubbly masses, cemented by ice, movement began because of melting and freezing of water, accompanied by consecutive changes in volume. In the region studied by Capps, one can observe all the stages of evolution he described, beginning from unquestionably active glaciers, ending with short rock glaciers, to typical rock glaciers in valleys where snow melts completely in summer.

Studies of Swiss rock glaciers conducted by Chaix are of interest because of their detail. They are particularly interesting because Chaix (for the first time in the history of the study of rock flows) studied their speed. Therefore, we deem it necessary to discuss boulder flows of the Swiss National Park in as much detail as possible, since, as far as we know, there is no information about them in Russian literature.

Chaix's studies, performed in the summers of 1918, 1919, and 1921, established the existence of four boulder flows in the Swiss National Park. The two largest, in the alpine Val Sassa and Val dell'Acqua, were studied in detail and photographed in 1:2500 scale.

Val Sassa is located between 2,000 and 2,500 m absolute altitude. The previous spread of the glacier in Val Sassa is demonstrated by two high side moraines extending almost the entire length of the valley. But where one might expect the last moraine, the glacial bed continues, becoming a tongue of gravel, which is the most typical part of a boulder flow. The tongue ends in a blunt, steep slope (about 40°), rising 20 m above the valley floor (fig. 3). The shape of the frontal slope, clearly seen in the photograph, evidences forward movement. The top of this slope, completely straight, forms a specific angle with the top of the surface flow; its bottom

forms a specific angle with the flow substrate. Obviously, if there were no motion, this clearly defined frontal slope form would not be preserved. It would be leveled by denudation processes if it were not continuously renewed. The frontal slope's form is renewed by the crushing of boulders from the upper surface of the flow. This indicates that the flow's surface moves more quickly than its deeper masses.

The middle segment of a rock flow differs from the lower segment primarily in that it is framed by side moraines. The valley floor, at its upper segment, is filled with snow.

Ridges from 50 cm to 1 m high, divided by furrows, run parallel to the edges of the flow along its length. The middle of the boulder flow surface exhibits transverse, concentric /107 ridges bent downward.

Rubbly material in the rock flow surface consists of sharp rocks averaging two fists in size. Excavations to a depth of 1.2 m in the bottom segment of the boulder flow (near its end) indicate the presence (beginning from above) of a layer of sharp rocks 10-20 cm thick. Below is a thin horizon of noticeably smaller rocks merging downward into a dense, blackish, moist soil mass mixed with a multitude of sharp rocks of all sizes.

The second National Park boulder flow studied is the most effective. It is a flow in the small Val dell'Acqua at an absolute altitude of 2,200-2,400 m. From 700 to 800 m long, it is 150 m wide in places. The scarp rock flow front rises 25 m above the valley floor (fig. 4). The upper segment of Val dell'Acqua (beginning with horizontal at 2,450 m) resembles the upper part of the Val Sassa: there is no rock flow, and the glacial bed is framed by side moraines ridged above slope scree. Within the lower segement (i.e. below 2,337 m) of the Val dell'Acqua boulder flow, its typical surface forms are bent ridges separated by furrows (fig. 5).
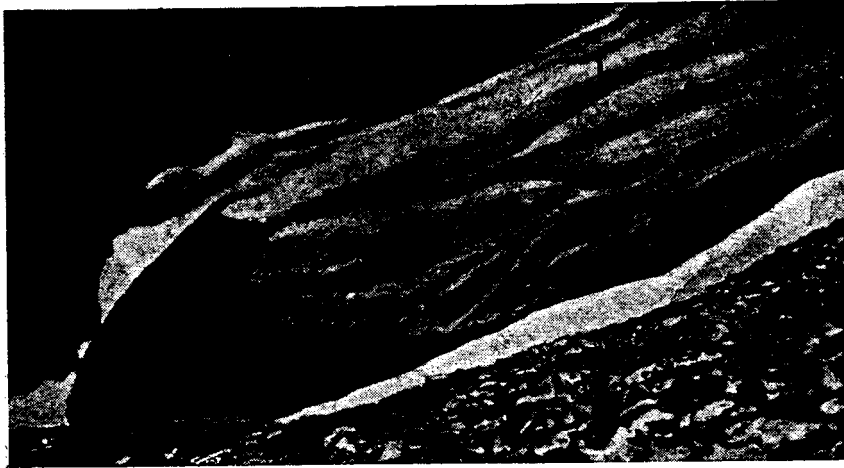
Fig. 3. The end of the Val Sassa boulder flow in the Swiss National Park.

Two larger ridges rise as scarps and give the impression of a small flow on top of a large one. The surface of the rock flow's middle segment (from 2,337 m to 2,378 m) is characterized by several longitudinal ridges. The right slope of the largest ridge is bounded by a narrow, deep furrow distinguishable for 350 m. The upper segment of the rock flow (from 2,378 m to horizontal at 2,450 m) has a surface not as steep, with stranger forms. Here, within the undulous surface are several closed depressions filled with water. These deepenings probably formed /108 as a result of the melting of the remaining ice buried beneath the gravel (ice was detected in a nearby locale). Near 2,416 m, the flow's surface becomes an unordered set of elevations and furrows.

Movement of rock flows in the Swiss National Park was first established by Chaix in the following primitive way. A stick /109 was driven into the base of the rock flow slope. After two days it was overturned by several large stones; several days later, it was entirely buried under the flow's fragmental mass.

In the summer of 1918, reference points were established and markers placed on the Val Sassa boulder flow. Near an elevation of 2,297 m, 16 flow rocks were painted red along a straight line between the reference points (on opposite
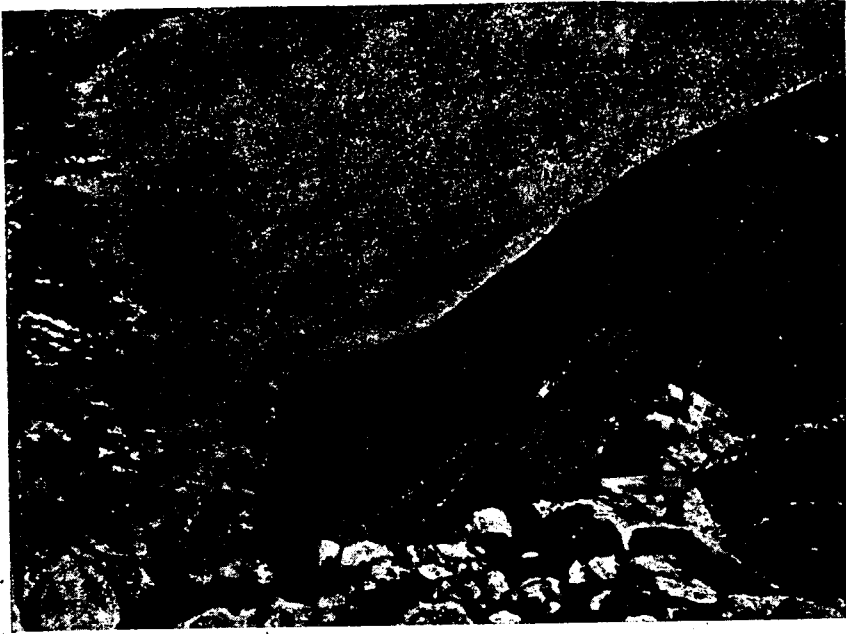
Fig. 4. End of the Val dell' Acqua boulder flow in the Swiss National Park.

Fig. 5. Boulder flow in the Val dell'Acqua.
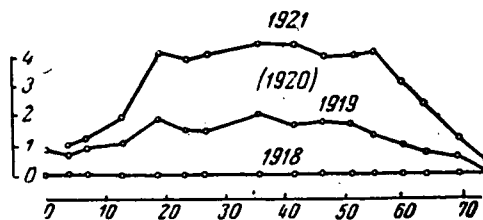
Forward motion in m

Distance between reference points, m.

Fig. 6. Movement of lines of reference points on the Val Sassa boulder flow.

sides).* In 1919, the line of painted rocks was surveyed, measurements were taken, and a new set of rocks was painted brown. This work was repeated in the summer of 1921, when another set of rocks was painted yellow.

Figure 6 gives an idea of the nature of forward movement of the Val Sassa rock flow. Data in fig. 6 and table 1 make it possible to conclude that the nature of the rock flow's forward /110 movement is similar to that of a glacier. A wide middle stria, constituting about half the total width of the rock flow, exhibits the following speeds: 1.3-2 m during the first year and 1.05-1.37 m in subsequent years. The average speed of eight reference points in the middle of the flow was 1.35 m per year. This middle stria of the flow is, as indicated above, characterized by curved ridges. Reference points exhibiting the greatest movement were on these ridges. In the two outside striae, each of which constitute one-fourth the flow's total width, speed slackens. Note that these outside rock flow striae are characterized by longitudinal furrows. At the end of the flow, trenches are arranged in a fashion similar to outside glacier cracks.

In 1918, two rows of rocks on the surface of the Val dell'Acqua boulder flow were painted to observe its movement. Markers were surveyed in 1919 and 1921. Table 1 (column 3) shows that the outer zone of the flow moved more slowly than the rest. The highest established speed during the first year was 1.55 m. Average speed during subsequent years equaled 1.35 m. However, conclusions based on observations of the lower row of markers do not have the desired accuracy. The fact is that one of the rocks disappeared in 1919; two more in 1921. The top row of rocks yielded more complete results. Here, just as in the Val Sassa flow, the presence of outer zones with slower

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*In Chaix's opinion, maximum error possible in using this
 measuring method is 10-15 cm.

TABLE 1

MOVEMENT OF REFERENCE POINTS ON ROCK FLOWS OF THE
SWISS NATIONAL PARK (A. CHAIX) (IN M)

Val Sassa		Val dell'Acqua (верхний ряд) 1)		Val dell'Acqua (нижний ряд) 2)	
3) Л е в ы й б е р е г					
1918— —1919 гг.	1919— —1921 гг.	1918—1919 гг.	1919—1921 гг.	1918— —1919 гг.	1919— —1921 гг.
0.85	4) выпали	0.23	0.55	0.65	—
0.65	0.25	0.65	1.80	1.10	1.90
0.95	0.20	0.85	1.95	1.10	2.70
1.00	0.90	1.05	2.20	1.10	2.30
1.75	2.10	1.10	1.90	1.45	1.90
1.50	2.40	0·95	2.70	1.35	2.40
1.45	2.55	1.23	2.60	1.50	2.35
2.00	2.30	1.00·	2.50	1.48	2.35
1.70	2.60	1.00	2.55	1.18	2.45
1.75	2.25			1.50	2.70
1.55	2.30	5) движение суммарное за 3 года		1.55	—
1.30	2.75			—	—
1.00	2.05	4.70		—	—
0.85	1.60	?		—	—
6) П р а в ы й б е р е г					
0.60	0.55	4.30		—	—
0.00	0.40	3.20		—	—
—	—	1.60		—	—
—	—	1.70		—	—

KEY: 1) Upper row; 2) Lower row; 3) Left bank; 4) Fell;
5) Total movement over 3 yr; 6) Right bank.
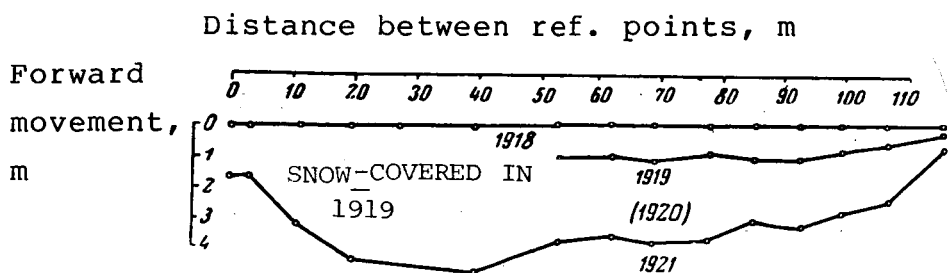
Distance between ref. points, m

Forward movement, m

Fig. 7. Movement of reference points on Vall dell' Acqua boulder flow.

motion was demonstrated. However, these zones constituted
one-fourth the total width. Their absolute width was almost
equal: 17 and 17.5 in the Val Sassa flow, and 20 m in the Val
dell'Acqua flow. The smallest demonstrable speed was 23-25 cm
(left bank) and 53 cm (right bank) per year. The greatest

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distance traveled in 3 years was 4.7 m, i.e. 1.56 m per year
(fig. 7). Comparison of the diagrams (fig. 6 and 7)
illustrating the movement of the Val Sassa and Val dell'Acqua
rock flows shows that, during the first year of observations,
the Sassa flow and the lower line of the Val dell'Acqua flow
move more quickly, while, during the next two years, the upper
reference points of the dell'Acqua flow exhibited the highest
speed. Chaix notes that dry weather predominant in 1921
apparently had no effect on the speed of the flows and that
small differences in reference point speeds could have depended
on their arrangement.

Movement is explained by certain morphological features of /111
the boulder flows. These features are not inherent exclusively
in rock flows, but are found also in lava flows, falls and
slides, landslides, and various forms of solifluction.

In Chaix's opinion, rubbly material in National Park
boulder flows is morainic deposits which previously occupied
glacial beds.* The glacier which filled Val Sassa receded and
left in its bed a thick layer of gravel mixed with layered
deposits and, possibly, masses of dead ice separated from the
glacier. These masses began to slide downward. As a result,
the frontal part of this massive flow left the framework of side
moraines. This movement continues in our time at a rate of
about 1 m per year, as observations during 3 consecutive years
shows. Having assumed that the rate of movement was as before,
and keeping in mind that the distance between the lower ends of
the side moraines and the end of the boulder flow was 100 m, we
can conclude that movement began about 100 years ago. This
coincides rather well with the probable age of the moraine.

Unlike gravel flows of the group described previously and
below, whose rubbly masses are continuously supplemented by

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* No drilling was done in National Park boulder flows.

erosion processes, rock glaciers now are almost never supplied with additional rubbly material. In all probability, only avalanches play a definite role in feeding coulées de blocs in the Swiss National Park.

Valleys and furrows on slopes sometimes appear via avalanches. According to Chaix's observations, at the end of summer the remains of avalanche snow are still visible, covering a significant area at the tops of the Val Sassa and Val dell'Acqua boulder flows. Chaix also notes that the surface of certain sections of the Swiss rock flows are literally strewn with fine gravel, piled in the same miraculous way on all flow boulders. Chaix rejects the possibility that Swiss National Park rock flows are fed by rubbly material from alluvial deposits. Indeed, the possibility of this sort of supply is excluded in all rock flow segments where it is framed by high side moraines which separate it from valley slope alluvial deposits. The valleys' upper segments also exhibit no alluvial deposits which merge into boulder flows.

Chaix's excavations on the Val Sassa boulder flow shed a some light on the causes of the movement of the Swiss boulder flows. The nature of the movement is to a certain degree attributable to masses of moist, fine soil in the boulder flows.

This circumstance, as well as physicogeographical conditions in Swiss valleys filled with boulder flows -- their alpine nature and the snow cover in their upper segments -- make it possible to presume that solifluction plays an unquestionable role in the processes by which these rubbly masses move.

Rock flows of the type described have been noted in other areas of the Alps. In Dössenthal (Tauern), Martonne [22] observed a small glacier in the process of disappearing. It /112 was extended more than a kilometer by rock glacier deposits.

We know of the existence of rock glaciers in the French
Alps from Alliks [6]. The tongue of the Mont de Lans (French
Alps) Glacier, buried under a cover of black slates, is an
actual rock flow (coulée rocheuse) for its last 500 m. Similar
forms in different stages of evolution (glaciers rocheux,
coulées rocheuses) of glacial origin exist in the Dauphine
Alps. Studying them makes it possible to satisfactorily explain
certain peculiarities of the "distorted" morainic relief.
Alliks especially notes the splendidly developed rock glaciers
in the northern cirques of the Combeynot Mountains.

Gravel flows of the Northern Pamir, described by K. K.
Markov [5] closely resemble certain rock glaciers in Alaska.
Such, for example, are gravel flows of the slopes of the Kainda
River Valley which abut the ends of the glacier. According to
Markov, in all more or less significant side valleys of the
Northern Pamir, "morainic forms are grouped linearly along the
valley floor in the form of long striae, strongly resembling
so-called stone rivers or rock flows... The flow of sandy-
rubbly material here may have a vertical effect of hundreds of
meters, and the low point at which these moraines occur can give
a completely different picture of the elevations to which
glaciers descend."

Let us mention that, in the Val Sassa of the Swiss National
Park, this vertical effect is, as indicated above, hundreds of
meters. Cases of mixing of rock flows and moraines are common.
For example, the de la Valetta boulder flow in the Swiss
National Park appears at the last moraine on the geological map.

Martonne [22], in his "Morphological Role of Snow in
Mountains," indicates that certain rubbly deposits in the
Carpathians, which he decided not to classify as moraines, must
in fact be rock glacier boulder flows.

Certain gravel flows of the Northern Pamir described by

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Markov [5] can serve as an example of transitions between rock glaciers and our first group of gravel flows. These are flows above which "there is neither glacier nor névé, but there are gravelly cones of scree. These gravel flows, containing much fine soil and which have a morainic nature, have surfaces strewn with alluvial shale. Here the "process by which morain-like material accumulates has now been replaced by the accumulation of sharp gravel rolling down from slopes."

Pamir "gravel glaciers" (Schuttgletscher) described by Finsterwalder [31] represent a whole chain of transitional forms, among whose links are glacier-like gravel bodies (Schuttkörper) totally unrelated to modern glaciers. Ice is not directly detectible in them; it reveals itself only in the wetness of the gravel and small puddles in surface depressions. Although the movement of these gravel glaciers has not been directly proven, the very nature of their steep frontal slopes, from which boulders break off, makes us assume that they are not immobile gravel segregations. If they contain ice, the gravel /113 cover protects it from normal ablation, due to which these gravel glaciers can move much farther than normal glaciers. According to Finsterwalder, these gravel formations often end hundreds of meters below modern ice tongues.

The group of gravel glacier transitional forms indicated by Finsterwalder leads to another marginal link -- to the gravel-strewn ends of Turkistan glaciers.

IV

Gravel flows occurring in connection with rock falls should be isolated into a separate group. Remarkable rock flows in this category were described by Cross and Howe (under the name "rock streams" in the San Juan Mountains of Colorado).

The floors of many glacial cirques in the San Juan

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Mountains are covered with huge segregations of rubble distinguishable from scree primarily in their flow-like form.

These rubbly segregations take the form of long tongues or lobes extending from the base of cirque walls to the latter's flat or slightly sloped walls. They end in a steep, pronounced front. The rock stream surface, rarely smooth, is described by 1) mounds separated by narrow depressions and 2) concentric ridges. Rubbly material comprises sharp boulders of various sizes. Boulders up to 15 feet or more in cross section are common. When viewed from a distance, many of these formations seem to resemble glaciers completely buried under rubbly material and descending from the cirques to the valleys.

One of the largest rock flows in the San Juan Mountains is the Pearson Basin rock stream. It consists of rhyolite fragments of the Potocsi volcanic series. The fragments ranger in size from huge boulders to coarse sand and grit. Most fragments measure from 1 to 2 feet in diameter and are angular in shape. Flow is restricted by abrupt, steep slopes. The middle of the flow's surface contains numerous round mounds separated by depressions. This interior hilly area is encompassed from the outside by long concentric ridges roughly following the outline of the edge of the flow. The crest of the rock stream is at the base of the cirque wall scarp.

The largest rock flow of the nearby Silver Basin differs from the Pearson Basin rock stream in that, instead of unordered, scattered hills, concentric ridges generally parallel to the outer edge of the flow predominate on its surface. When viewed from a certain distance, the flow surface exhibits a surprising similarity to the surface of a viscous lava flow (pahoehoe), particularly of the Hawaiian type.

At first glance it seems that Colorado rock streams and Alaskan rock glaciers described above are phenomena of the same

order. Both types are formed by angular fragments and are quite
similar in terms of their general appearances and surface
details. Photographs of San Juan Mountain rock streams also
exhibit the astounding external similarity of these rock flows
to boulder flows of the Swiss National Park: the same shape of /114
frontal and side slopes, the same surface shapes -- concentric
ridges, longitudinal ridges, unordered hills or mounds.
However, these morphological features of rock flows are also
typical of certain slides, mud flows, and lava flows. Inherent
to forms of entirely different genesis, they are attributable
exclusively to the movement of masses of a specific consistency
-- viscous masses.*

In the "Silverton Folio," published in 1903, Cross and Howe
attribute a glacial origin to rock streams, saying "The largest
rock streams must still owe their origin to glaciers. No other
agents could have transported such huge masses of rubble so far
from their place of origin." In a work published later, Howe
rejected the views he had espoused previously, reaching entirely
different conclusions -- namely that San Juan Mountains rock
streams form in connection with rock falls.

Rock falls in the San Juans occurred because of the
disappearance of glaciation. The sites of falls were cirque
walls, which, freed from diluvial ice masses, should have had an
extreme grade. Similar relations were established by A. Penck

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* Transverse movement ridges (Bewegungswülste) are also
  observed during massive shifts on very flat slopes.
  According to W. Penck, materials segregated in small
  valley-like depressions (Talungen) of the true surface in the
  Stambul region, which form hard, immobile masses more or less
  rich in rocks during the dry season, start to move and emerge
  from the valley in winter (during drenching). The sod breaks
  up, and clumps take part in the formation of transverse
  ridges.

and Bruckner for the Alps. That rock streams exist in some cirques and not in others is explained by the peculiarities of the petrographic order. Most rock streams are confined to an area where volcanic rocks develop; fewer, to areas composed of granites, shales, and quartzites. Rock falls which formed rock streams were classified as a type of cliff fall (A. Heim's Felsstürze). These were falls of extremely crushed masses, whose vertical drop was accompanied by horizontal ricochet. The sort of horizontal movement of the fragmental masses that takes place during certain rock walls is no longer in doubt after testimony of witnesses to the Elm and Frank falls and studies by A. Heim.

W. Penck [23] presents the very occurrence of a gravel flow as follows: "A complex of rock breaks into fragments during the fall, and these fragments no longer slide, but roll, tumbling one over another. If the moving mass of rock is large, fragments combine with the rushing gravel flow (Schuttstrom).... The gravel flow, similar to soil avalanches, stops suddenly, as soon as its active force is depleted." This phenomenon was first noted during the Elm rock fall (11 September 1881), which is classed as a cliff fall. The Elm gravel flow was 1,400-1,450 m long and from 400 m (between Unterthal and Elm) and 500 m (between Müsli and Eshen) wide. The speed of the flow /115 fragments, which included monstrous boulders*, was about 120 m per second.** The thickness of the flow's rubbly mass could not be directly measured. It was estimated as at least 40 m. It should be particularly emphasized that the gravel flow had absolutely nothing in common with a mud flow.

In the first days after the fall, the rock flow's surface

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* One boulder at the bottom of the rock flow was about 15 m
  long, 12 m wide, and 7 m tall, which corresponds to a volume
  of 1,260 m^3 and a weight of about 3,330 tons.
**According to A. Heim's calculations.

was completely dry, and the gravel was covered by about 2 cm of dust. It is noteworthy that the base along which the gravel flow moved had only a 3-5° grade. The movement of huge dry rubbly masses along so flat a base for more than 1,400 m on a horizontal plan is highly improbable. According to Heim [16], this sort of movement was possible only if the soil cover of the entire segment of the valley between Unterthal, Müsli, and Eshen, thoroughly softened before this by torrential rains, had acted as a lubricant for the movement of the rock mass. The latter, fallen onto this sliding base, developed a miraculous active force. Testimony by witnesses also confirms that gravel masses in Müsli did not roll, but slid.

One other circumstance confirms that the gravel flow's movement, in contrast to W. Penck's assertions above, is not rolling, but sliding. The very nature of the movement of rock flow rubble as a single mass was severely restricted on all sides and resembled certain large avalanches, a glacier, or even more, a lava flow. Nowhere was it observed that individual rocks went beyond the flow's boundaries, which would be inevitable during rolling. At Duneberg, the huge gravel mass broke up abruptly and suddenly. The nature of the movement was then related to the fact that no one was injured during the Elm rock fall. The gravel flow completely crushed everything in its path, but left entirely undamaged everything beyond its limits. Without describing the details of the flow's surface, Heim notes that, in appearance and structure, this momentarily rushing gravel flow surprisingly resembles a lava flow, glacier, and other forms described by substantially slower movement.

The Frenk fall (29 April 1903, Canada), also a Felsstürze, had all the essential characteristics of the Elm fall. Huge masses of rock (mostly limestone) fallen from the very highest central peak of the Turtle Mountain Range, were crushed into rubble which literally plowed up the bottom of the Old Man River Valley and rushed 400 feet up the opposing terraced slope. The

rubbly masses moved as does a viscous liquid. The rubble flow, moving along the flat surface, had a tendency to expand. Encountering highlands on their route, the moving masses strayed from a straight path and flowed along the obstacles. The overall appearance of the rubbly mass of the Frenk fall exhibits surprising similarities to San Juan Mountains rock streams. Boulders, sometimes reaching a length of 40 feet, form hills and short transverse ridges. The segregation of rubbly masses ends in a precipitous slope 6-30 feet high.   /116

Let us present one more example -- a rock flow which occurred during a fall (also a Felsstürze) in the group Brent and Southern Tyrol in May 1882. The most surprising thing about this fall was that fragments of hard, white limestone from the broken cliff fell from the rocky walls to the valley as does water, in cascades. The rock flow was separated into three branches, which now lie as three white rock glaciers on the valley's green meadows.

According to Jules Blache, rock flows arising because of falls are quite common in Chartres. Fallen masses of rock descend as rock "avalanches," cutting clearings in forested slopes. In Chartres, these phenomena are varied, including wall-like flows moving relatively slowly and inundating tree trunks on their path with dirt.

Rock flows arising because of falls in the Central and Western Tien Shan have also been described by Friederichsen and Machatschek. The recess where the gravel masses of the large, typically developed gravel flow studied by Mahacek separate is in the area where thin plastic and extremely fragile upper Devonian limestone shales develop. Rock flows below the separation recess on a flat, slightly sloped surface constitute a gravel mass with sharp edges and convex surface striated by parallel ridges perpendicular to the direction of movement. In general, Schuttströme described by Machatschek are very similar

to San Juan Mountains rock streams.

Machatschek's and Howe's views on the origin of this sort of gravel flow differ in the following sense: in Machatschek's opinion, gravel flows are not formed directly by rock falls. The latter merely supply rubbly masses. This entire rubbly mass starts to move and takes the form of a flow due to intense drenching. This drenching is enhanced both by the properties of the rock in the region of the Western Tien Shan studied by Machatschek (extremely high fracturing of the rocks) and by climatic conditions (extremely rapid melting of the snow cover, limited precipitation during melting).

Howe describes one very interesting form of rubbly material, common in the San Juan Mountains, which may be considered an intermediate form between gravel flows of the category discussed here and scree. Rubbly segregations of this type, quite similar to ordinary screes, differ from the latter in that they have a steep, bank-like scarp similar to that of rock streams. Howe [19] explains the formation of these forms, developed at the base of scarps facing north, as follows. North-facing cirques are suitable sites for the development and more prolonged existence of so-called snow banks which cover the foot of scarps. In the beginning of summer, one can often see such snow banks with surface strewn with fragments which have fallen from the cirque wall scarps. Fragments falling onto the smooth, inclined surface of the snow roll farther from the base /117 of the scarp than when they fall from the slope of a scree. During summer months, when the snow bank disappears, the process by which fragments separated from the scarp accumulate will proceed just as it does in an ordinary scree. The process of fragment pile formation is illustrated by a diagram presented by Howe. The form resulting from this type of accumulation will naturally be much more complex than an ordinary scree: longer and ending in a steep front, these rubble piles will approach the form of a rock flow.
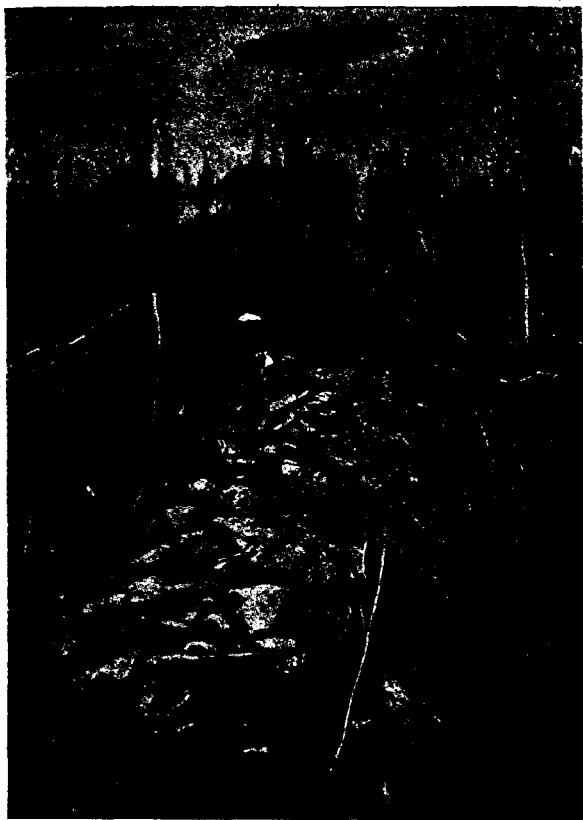
Fig. 8. The bottom of a rock stream on the southern slope of Poachvumchorr (Khibina) (photo by E. G. Vokken).

This group may also include one type of rock flow which occurs, just as in the case of rock falls, as a result of the free fall of rock fragments. The regular, systematic fall of fragments (so-called Steinschlag) separated as a result of intense erosion (temperature, frost) from denuded cliff walls, is, as we know, a common phenomenon in alpine regions. The paths along which fragments move are channels descending from cliff walls (so-called Steinschlagrinnen). Fragments forming ordinary deposits in the form of a gravel cone at the end of the channel can accumulate in the same channel as rock flows. Rock falls may also be combined with "Steinschlag" phenomenon, i.e. with the regular fall of relatively small fragments. Certain rock flows in the Khibinsk Mountains apparently took place precisely in this way. An example is one of the gravel flows on the southern slope of Poachvumorr (fig. 8).

The rubbly material of a rock stream consisting of sharp boulders 30-70 cm in cross section lies quite loose.

At its top, a gravel flow may occupy a pronounced trough-shaped furrow. Down the slope, the furrow filled by the rock stream is identifiable as a straight clearing in the forest. The bottom of the furrow here is formed by plates of bedrock bearing traces of corrosion. The plates' surface seems somehow rough-finished.* The drop of the furrow bottom at this /118 segment equals 40-50°. There is no rubbly material whatsoever here: the plates' surfaces seem polished. Below, the rock stream becomes a narrow (about 3 m) flow of sharp boulders (30-50 cm in cross section) occupying a sharply defined furrow. Bedrock raised by a steep scarp above the crest of the rock flow exhibits traces of recent falls (fresh surface ruptures). The rock flow itself is in all probability formed by a cliff fall (Felsstürze), whose fragments descended in several branches. The rock flow's sharply defined ravine should be considered the most hazardous (within the vicinity of the USSR Academy of Sciences' mountain station) route for rock falls (a formation similar to the Steinschlagrinnen of alpine regions). This is confirmed by observed changes in the arrangement of markers placed there. These changes amount to the presence of large or small breaks in the chain of painted rocks. Breaks in the chain of painted rocks are in all likelihood caused by fragments falling from above which have separated as a result of erosion from the rocky walls in the crests of ravines filled with gravel.

Heim notes that gravel flows caused by certain rock falls continue to move slowly for a week or even a year. He presents as an example the Brients rock flow in the canton of Graubunden. This flow, stationary for weeks, moved several centimeters, and sometimes even several meters per day during wet periods.

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* Only within this segment can one observe traces of corrosion. In other places, there is no physical possibility of removing large boulders and rocks which fill gravel flow furrows.

Heim considers the Elm rock fragment flow immobile. The declivity of the base, in Howe's opinion is too insignificant for these coarse rubbly masses -- even if completeley drenched -- to continue to move slowly.

Studies of San Juan Mountains rock streams conducted during several field seasons are, in Howe's opinion, insufficient to prove their movement. Nonetheless, on the basis of factual material presented by Howe, we can, with high probability, presume that the rock streams he described are in movement and that a factor in this movement is solifluction, which acts on the flow in early spring in high San Juan Mountains basins.

The particular interest in gravel flows resulting from rock falls stems from the mechanical work they perform. These rapidly rushing rock flows develop their path and deepen it only slightly. During a fall in the Glarus canton (29 April 1868) a flow of fragments developed a furrow 6-10 m wide and 10-20 m wide. A stream of cliff fragments from the Elm fall performed the same mechanical work. W. Penck compares the rock flows' mechanical action on the base along which they move, which is manifest within the limits of the path, to erosion of a water current with which it also shares this common mechanism.

In conclusion, let us present a classification of rock flows. It is based on the difference in genesis of their rubbly masses and on an attempt to identify for each group three regions (feed region, path region, and deposit area) typical for all forms of mass movement (table 2).

TABLE 2

Group	Feed area	Drainage and deposit areas	Examples (types)
I Gravel flows	Supply -- from fragment masses formed during normal rock formation Fed from the crest of gravel flow	Branched system of boulder flows at valley floors, similar to river systems (stone rivers).	Stone rivers of Falkland Islands, Urals stone rivers
		Simple (unbranched) boulder flows on valley floors.	Spitsbergen boulder flows
		Rock flows of less coarse (than in boulder flows) material in trough-shaped ravines of slopes.	Upper Engadin (Alps) rock flows
II Boulder seas	Fed at the rocky base of fragmental accumulations	Stream-like stria of rocks or boulders in trenches of steep slopes Boulder occlusions covering areas on slopes of a certain grade	Boulder stria on Spitsbergen, Scandinavian mountains. Rock stria of the Khibinsk Mts. Boulder seas of German mid-altitude mountains, Uruguay, Anatolia. Arctic and alpine boulder seas. Subarctic boulder seas of Northern Sweden, Khibinsk Mountain rock seas, etc.
III Rock glaciers (A series of transitional forms relate this group to gravel flows of the first group -- actual glaciers.)	Consists of morainic material beneath whose cover ice is found (solid masses or "intermediate" ice, i.e. filling interstices between fragments. A continuation of active glaciers or no modern supply of fragmental material.	Glacier-like gravel masses occupying the beds of glacial valleys and ending in a typical steep front.	Alaska rock glaciers. Boulder flows (coulées de blocs) of the Swiss National Park. Glaciers rocheux of the French Alps. Rock flows and gravel glaciers (Shuttgletscher) of the Pamir)

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Group	Feed area	Drainage and deposit areas	Examples (types)
IV Flows of rock fall fragments.	Fragmental material from Fels-stürze-type falls. Glacial cirque walls	Long tongues or spades of fragmental cirque wall bases and ending in a steep front	Rock streams of the San Juan Mts. in masses advancing from Colorado.

	Separation recesses where highly cracked rock develops.	Flow-like or gla-cier-like, steep-sloped convex gravel masses ending in abrupt, steep front.	Elm gravel flow.
			  Frenk fall (Canada) fragmental masses.
			  Rock fall fragmental flows in the Brent (Tyrol) group. Rock flows of Chartres. Gravel flows of Central and Western Tien Shan.

Transitional forms and scree.	Cirque walls.	Fragment piles differing from scree in length and the presence of a steep frontal slope.	Widespread fragment of the San Juan Mts.
IVa Gravel flows re-sulting from re-gular falls of fragments (Stein-schlag phenomena) sometimes com-bined with rock falls (transform-ing into gravel flows of the first group.	Fed by intensively weathered rock outcroppings in the form of steep scarps (cliff walls) on mountain slopes	Stria of fragments filling channels (Steinschlagrinnen), descending from rocky scarps along steep slopes.	Certain rock flows of the Khibinsk Mts. Rock flows of alpine regions.

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